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Assessing Opportunities in Nitrogen Management for GHG Emissions Reduction in Agriculture Systems using A Life Cycle Assessment Model

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Abstract **-** Agricultural production systems are essential for food security, yet this sector remains a key driver of greenhouse gas (GHG) emissions. This study evaluates GHG emissions from corn production under varying nitrogen (N) management strategies. A Life Cycle Assessment (LCA) approach is applied within a cradle-to-farm gate boundary to quantify emissions from input production, on-farm operations, and transportation. The analysis integrates field measurements, producer surveys, and secondary databases, while the Cool Farm Tool (CFT) simulates GHG outputs across different fertilization and residue management strategies. Results show that pre-field activities, including fertilizer and seed production, account for 62% of total emissions, primarily due to their energy-intensive nature. On-field emissions represent 31%, mainly from soil nitrous oxide (N_2O), while post-field handling contributes 7%. Fertilizer type and application rate significantly influence emissions, with increasing application rates from 25 to 150 lbs/acre leading to substantial increases in fertilizer production and soil emissions. Residue management also plays a pivotal role, with anaerobic composting resulting in up to 11,300 kg CO_2e/ha, while residue removal produces zero emissions. Monte Carlo simulations reveal that soil emissions, particularly the emission factor, exhibit the highest sensitivity (θ = 0.79–0.86). Direct measurements of GHG fluxes, particularly N_2O and CO_2, are statistically analyzed using regression models, with CO_2 emissions showing stronger model fits (R^2 = 0.48–0.61) compared to N_2O emissions (R^2 = 0.3–0.46), reflecting varying sensitivities to environmental and management factors. These findings highlight the importance of optimizing N inputs, improving residue management, and refining emission factor estimates to mitigate the carbon footprint of corn production.

Keywords**:** Life cycle assessment, Nitrogen management, Greenhouse gases, Cool farm tool, Fertilizer application

1 INTRODUCTION

Agriculture remains a key contributor to global greenhouse gas (GHG) emissions, with Canadian agricultural activities alone accounting for an estimated 55 Mt CO_2-equivalent in 2020, approximately 7–8% of the nation's total emissions [1]. This sector's emissions are predominantly driven by nitrogen-related processes and carbon fluxes resulting from land use, fertilizer application, and livestock management. In the context of escalating global food demand and increasingly stringent environmental regulations, it is imperative to transition toward more sustainable and resource-efficient agricultural systems. Nitrous oxide (N_2O), a potent GHG with a global warming potential nearly 300 times that of CO_2, arises largely from the nitrogen fertilizers. Agricultural interventions such as crop residue incorporation, tillage intensity, and irrigation techniques all influence soil nitrogen dynamics and, consequently, GHG fluxes [2][3]. Numerous mitigation strategies have been proposed to reduce these emissions, including precision nutrient management, conservation tillage, diversified crop rotations, and the use of nitrification inhibitors [4] [5]. However, the complexity and variability of agroecosystems necessitate a holistic and quantitative approach for assessing the effectiveness of such interventions. Nitrous oxide (N_2O), a potent GHG with a global warming potential nearly 300 times that of CO_2, arises largely from the nitrogen fertilizers. Agricultural interventions such as crop residue incorporation, tillage intensity, and irrigation techniques all influence soil nitrogen dynamics and, consequently, GHG fluxes [3]. Numerous mitigation strategies have been proposed to reduce these emissions, including precision nutrient management, conservation tillage, diversified crop rotations, and the use of nitrification inhibitors [4][5]. However, the complexity and variability of agroecosystems necessitate a holistic and quantitative approach for assessing the effectiveness of such interventions.

Life Cycle Assessment (LCA) has emerged as a robust methodological tool to quantify the environmental impacts of agricultural systems across their entire value chain, from input production and field operations to post-harvest processing and transportation. LCA enables the identification of hotspots of GHG emissions and resource inefficiencies, thereby guiding targeted mitigation strategies [6]. Its application in nitrogen management allows for evaluating trade-offs between productivity and environmental sustainability, especially when integrated with spatially and temporally resolved field data. Despite these developments, several methodological gaps remain. First, many existing LCA studies rely on generalized or static emission factors that do not adequately reflect the temporal and spatial variability in N_2O emissions due to different fertilizer application techniques or soil-climate interactions [7−9]. Second, limited attention has been given to the comparative impact of nitrogen application quantity and timings on overall life cycle emissions, particularly within region-specific crop production systems [8][10]. Moreover, while some studies emphasize the role of improved agronomic practices, there is often insufficient differentiation between the types of fertilizers used (e.g., urea, ammonium nitrate, enhanced-efficiency products) and their distinct environmental footprints within a life cycle framework [11][12]. This limits the ability to make precise recommendations for optimized nitrogen management that balances crop productivity with emission reductions. Addressing these gaps requires a more nuanced, data-driven application of LCA that integrates diverse nitrogen strategies, accounts for site- and system-specific variables, and provides comparative insights across fertilizer regimes. In this context, the present study assesses how different fertilizer types, application strategies, and other factors affect nitrous oxide emissions in corn production systems using a life cycle assessment approach.

2 METHODOLOGY

This study utilized a Life Cycle Assessment (LCA) framework to quantify greenhouse gas (GHG) emissions associated with corn production under varying nitrogen management strategies. The assessment adhered to the ISO 14040 and 14044 standards, encompassing goal definition, system boundary setting, life cycle inventory (LCI) analysis, impact assessment, interpretation and validation phases as illustrated in Fig.1. The LCA accounted for direct and indirect emissions, integrating data on fertilizer types, application methods, energy consumption (fuel and electricity usage), and agronomic practices. Additionally, the Cool Farm Tool (CFT) was utilized to assess various scenarios involving different nitrogen and residue management practices.

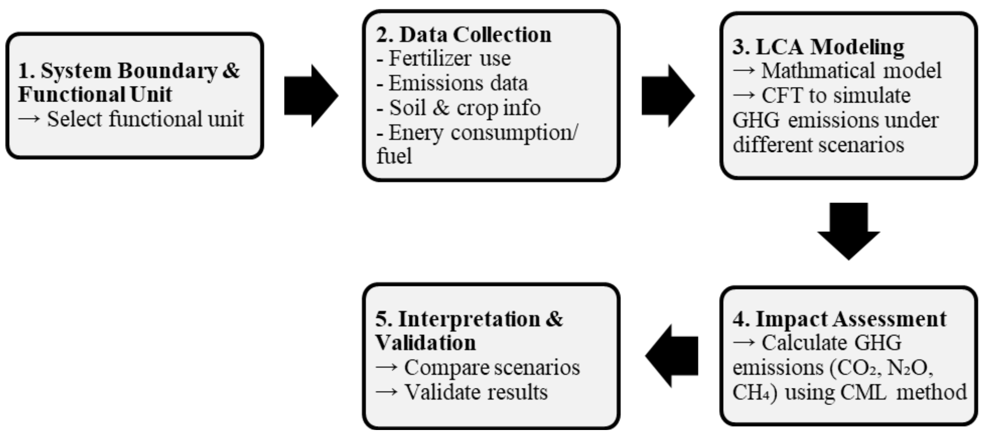

Fig. 1: Steps to quantify GHG emissions and evaluation of farming practices using a LCA approach.

2.1 Define System Boundaries and Subsystems

The analysis was based on a cradle-to-farm gate system boundary, which encompassed three primary life cycle stages: (a) Input production, covering the manufacture of seeds, fertilizers, and fuels; (b) On-farm operations, including soil preparation, sowing, fertilization, irrigation, pest management, and harvesting; (c) Transportation, limited to within-farm and immediate post-harvest logistics. The functional unit was defined as the cultivation of 1 hectare of corn, allowing for standardized comparison across nitrogen input scenarios and system configurations. Thus, all GHG emissions were converted to CO_2 equivalent and normalized using the functional unit.

2.2 Data Collection and Inputs

Environmental and operational data were compiled from field measurements, surveys, and established databases to support the life cycle inventory development. (1) Meteorological data were collected using Aeroqual sensors installed at multiple locations across the site to capture spatial variability in temperature, humidity, wind speed, rainfall, and barometric pressure. (2) Soil parameters, including temperature (°C) and volumetric moisture content (m^3/m^3), were monitored using HOBO MX2307 data loggers. (3) Management practices, such as tillage intensity, irrigation schedules, and pest control measures, were documented through structured farm surveys. Fertilizer information, including type and application method, was obtained from local market sources and directly from on-farm records, as these inputs play a critical role in determining nitrous oxide (N_2O) emissions. (4) Emission factors for upstream processes, including fertilizer manufacturing, seed production, transportation, and electricity generation, were sourced from the Ecoinvent 3.9 database and supplemented with values from relevant literature [1].

Case study: This study focused on a representative corn field located in southwestern Ontario, Canada, a region recognized for intensive corn and soybean production due to its fertile soils and favourable climatic conditions. Specifically, Field A was selected from the region that experiences a humid continental climate, with warm summers, adequate rainfall, and a growing season suitable for corn cultivation. The site was chosen due to its typical management practices, including the use of synthetic fertilizers and pesticide applications, which are broadly reflective of commercial corn production systems across eastern Canada. For study purposes, 1.4 hectares of area were used to collect data for life cycle inventory modeling.

2.3 Life Cycle Inventory Model

The relationship between inputs and emissions was modeled using a matrix-based linear system of equations, formulated as:

$$A \cdot X = Y \tag{1}$$

whereas:

A is a matrix of emission coefficients, each representing the emission rate associated with a specific input or process.

X is the vector of inputs (e.g., energy use, fertilizer, farming practices).

Y is the vector of GHG emissions (e.g., CO_2, N_2O, CH_4).

Using an inverse matrix method, the equation for Y (GHG emissions) was solved as follows:

$$X = A^{-1} \cdot Y \tag{2}$$

Here, A^{-1} is the inverse of the matrix A and allows us to determine the specific GHG emissions (CO_2, CH_4, N_2O) based on the inputs provided. This method allowed for scenario-based simulation, wherein multiple fertilizer types and application schemes were modeled independently to determine their respective emission footprints.

2.4 Environmental Impact Assessment

The environmental impact assessment in this study was conducted using the CML-Impact Assessment baseline 2016 methodology, this method follows a midpoint-oriented approach to evaluate specific environmental mechanisms such as climate change, eutrophication, acidification, and toxicity. The selected impact categories included global warming potential (GWP) over a 100-year time frame, eutrophication potential (EP), acidification potential (AP), human toxicity potential (HTP), and ecotoxicity potential (ETP). Life cycle inventory data on emissions and resource use were converted into equivalent environmental burdens using characterization factors from the CML-IA 2016 framework, such as kg CO_2-equivalents (CO_2-eq) for GWP and kg PO_4^{3-}-equivalents for EP. To facilitate comparative analysis across impact categories and agricultural activities, all results were normalized using regional normalization factors. These factors reflect the average per capita environmental load and enable the conversion of characterized impact values into unitless scores, making the magnitude of different impact categories directly comparable. This standardization supports an integrated understanding of trade-offs across climate, ecosystem, and human health domains.

Additionally, for a more focused assessment of climate-related emissions, a global warming potential (GWP)-specific metric was calculated over a 100-year time horizon, using the following characterization factors: $CO_2 = 1$, $CH_4 = 25$, and $N_2O = 298$. The total climate impact was computed as:

$$\text{Impact}=\sum (\text{Emission of gas} \times \text{GWP of gas}) \quad (3)$$

Where E_i represents the quantity of each emitted gas, and GWP_i is its associated global warming potential. This allowed for a direct comparison of nitrogen management strategies in terms of their contribution to climate change.

2.5 Decision Support Tool

The Cool Farm Tool (CFT) was employed as a decision-support emission modeling tool to estimate greenhouse gas (GHG) emissions associated with corn production under varying nitrogen management strategies. This empirical, farm-level calculator utilizes activity-based data inputs, such as fertilizer application rate and type, soil conditions, tillage practices, and climatic variables, to estimate direct and indirect emissions of CO_2, CH_4, and N_2O. Built on IPCC Tier 1 and Tier 2 methodologies (the globally recognized frameworks for GHG estimation, which use default and region-specific emission factors, respectively), the CFT accounts for emissions from soil processes, input production, on-farm energy use, and residue management. By simulating multiple nitrogen input scenarios, the tool facilitated the comparative evaluation of total GHG emissions across different fertilization regimes. Its built-in algorithms and emission factors, validated by peer-reviewed studies, enabled scenario testing that reflects both management-specific and site-specific emission outcomes, making it a practical tool for assessing mitigation potential in crop-based systems.

3 RESULTS AND DISCUSSION

3.1 Carbon Footprints based on Life Cycle Assessment

Life cycle assessment (LCA) was conducted using a projected yield of 4.2 tons per acre for corn production at Site A, incorporating a cradle-to-farm gate system boundary to evaluate greenhouse gas emissions across all key input and operational stages. As shown in Table 1, fertilizer manufacturing and residue management were primary contributors, releasing 251.91 kg CO_2e and 96.87 kg CO_2e per ton, respectively. Site A's energy demand was also notable: approximately 20 litres of diesel were consumed per ton of corn, emitting 53.6 kg CO_2e, while electricity use (15 kWh per ton) contributed an additional 2.75 kg CO_2e. Transportation, modeled as a 50 km haul, added 16.05 kg CO_2e per ton. Seed production was the most carbon-intensive input, contributing 1,971.1 kg CO_2e per ton. Soil-based emissions further amplified the footprint, with CO_2 fluxes at 5.50 Mg CO_2e per hectare and N_2O emissions at 566.6 kg CO_2e per hectare, values reflecting biological activity and site-level nitrogen dynamics.

In addition to these core categories, several ancillary sources of emissions were integrated. Irrigation energy use, though modest, was modeled at approximately 0.6 kg CO_2e per cubic meter of water applied. Pesticide and herbicide production contributed an estimated 25–30 kg CO_2e per kilogram of active ingredient used, depending on the formulation. Field machinery operations, including tillage and planting, added approximately 9 kg CO_2e per hour of use. Post-harvest handling and on-farm packaging activities, although often overlooked, contributed an additional 50–100 kg CO_2e per ton, depending on storage and processing conditions. The inclusion of these additional categories ensures a more complete representation of the corn production system's environmental impact and strengthens the methodological robustness of the life cycle assessment. This broader scope enables more accurate comparisons across systems and better identification of emission hotspots for future mitigation.

Table 1: CO_2 (equivalent) emissions inventory for corn production

Activities	Unit of Factor	Emissions
Pre-Production		
Fertilizer Production*	kg CO_2e / ton	251.91
Diesel Production*	kg CO_2e / L	53.60
Electricity Generation*	kg CO_2e / kWh	2.75

Transportation (On-road freight)	kg CO_2e / km	16.05
Seed Production	kg CO_2e / ton	1,971.10
Pesticide/Herbicide Production	kg CO_2e / kg active	25–30
In the Field		
Soil flux CO_2	kg CO_2e / ha	5,500
Soil flux N_2O	kg CO_2e / ha	566.60
Residue Management	kg CO_2e / ton	96.87
Irrigation (Water Pumping)	kg CO_2e /m^3 water	0.6
Field Machinery Use	Kg CO_2e / hr operation	9
Farm Building Energy Use*	kg CO_2e / m^2-year	2.5–6.0
Post-Production		
Packaging & Post-Harvest Handling*	kg CO_2e / ton processed	50–100

Note: *Data source and emission factors are based on GREET 2023, Ecoinvent 3.9.

Emissions in corn production were divided into three life cycle stages: pre-field (62%), on-field (31%), and post-field (7%). Pre-field emissions were driven mainly by seed production and agrochemical manufacturing. On-field emissions, dominated by soil N_2O, accounted for a significant portion due to microbial processes. Post-field emissions, though smaller, still contribute due to transport and handling, emphasizing the need for efficient input and sourcing strategies. When considering the contributions from specific on-field activities such as in Fig. 2, emissions from diesel biofuel blend usage (27.6%), mulching seeding of corn (31.2%), and the operation of manure spreaders (37.2%) stand out, with the remaining portion attributed to fertilizer spraying. The higher emissions from manure spreaders can be attributed to the use of larger, more fuel-intensive machinery and the energy required for transporting and applying the manure. In contrast, mulching typically uses lighter machinery and, while it provides benefits for soil health, it results in fewer emissions. Fertilizer spraying contributes the least to emissions, as it involves less fuel consumption with lighter machinery, and modern application techniques allow for more efficient and precise use of fertilizers. While fertilizer production can result in indirect emissions, the actual spraying process itself has a relatively low carbon intensity compared to other on-field activities.

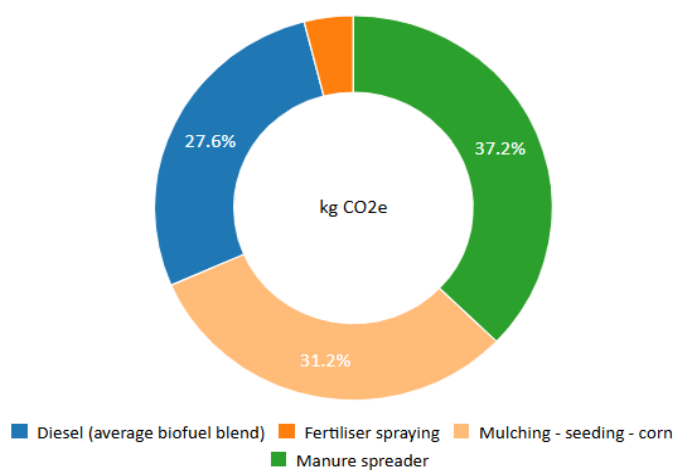

Fig. 2: Contribution of on-field activities to Greenhouse Gas emissions in corn production.

3.2 Evaluation of Nitrogen Management Impact on GHG Emissions

Fig. 3 shows a clear increase in greenhouse gas emissions with higher nitrogen application rates, both from fertilizer production and subsequent soil emissions. Two fertilizer types, Ammonium Sulphate Nitrate (ASN) and a 5-10-5 NPK formulation, were evaluated across three application rates: 25, 100, and 150 lbs per acre. In the case of ASN fertilizer (26%

nitrogen), fertilizer production emissions increased substantially with application rate, from 94 kg CO_2e at 25 lbs/acre (Treatment 1) to 720 kg CO_2e at 100 lbs/acre (Treatment 2) and reached 1200 kg CO_2e at 150 lbs/acre (Treatment 3) as shown in Fig. 3 (a). Soil emissions showed a similar trend, rising from 54 kg CO_2e (Treatment 1) to 420 kg CO_2e and 670 kg CO_2e under Treatments 2 and 3, respectively. No emissions were recorded in the control condition (no fertilizer treatment). Comparable results were observed using 5-10-5 NPK fertilizer (containing 5% nitrogen, 10% phosphorus, and 5% potassium). At an application rate of 25 lbs/acre, emissions from fertilizer production and soil were 155.45 kg CO_2e and 51.79 kg CO_2e, respectively as shown in Fig. 3(b). These emissions increased to 621.79 kg CO_2e (production) and 207.16 kg CO_2e (soil) at 100 lbs/acre, and further to 932.69 kg CO_2e and 310.73 kg CO_2e at 150 lbs/acre. These trends can be attributed to two key mechanisms: (1) increased upstream emissions associated with the energy-intensive production and transport of nitrogen-rich fertilizers; and (2) elevated microbial activity in soils with higher nitrogen availability, leading to greater emissions of nitrous oxide (N_2O), a potent greenhouse gas. The findings emphasize the significant environmental cost of intensive synthetic fertilizer use and underscore the importance of optimizing nitrogen application rates for climate-smart agricultural practices.

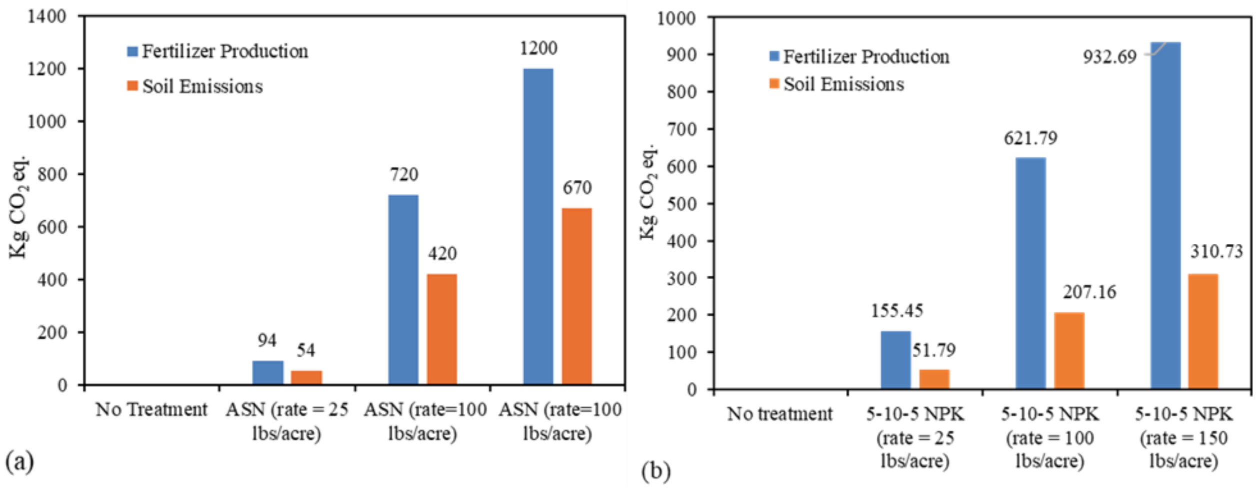

Fig. 3: Greenhouse gas emissions (CO_2e) from fertilizer production and soil processes under varying application rates of (a) Ammonium Sulphate Nitrate (ASN) and (b) 5-10-5 NPK fertilizers

3.3 Emissions and Residue Management

Residue management plays a critical role in determining on-farm greenhouse gas (GHG) emissions, as post-harvest biomass can either decompose aerobically or anaerobically depending on the management approach. In this study, all results are simulated using Cool Farm Tool to estimate CO_2 equivalent (CO_2e) emissions per hectare for various residue management scenarios. The simulations show substantial variation across practices as shown in Fig. 4. Removing residues from the field for reuse resulted in zero emissions, confirming it as the most climate-friendly option. In contrast, the highest emissions (11,300 kg CO_2e/ha) occurred when residues were removed for composting without forced aeration, due to anaerobic conditions that generate high levels of methane (CH_4) and nitrous oxide (N_2O). Similarly, leaving residues untreated in heaps or pits produced 8,040 kg CO_2e/ha, also attributed to anaerobic microbial activity. Forced aeration composting, which maintains aerobic conditions, significantly reduced emissions to 723.44 kg CO_2e/ha. Lower emissions were also observed from burning residues in the field (341.28 kg CO_2e/ha) and leaving them distributed or mulched (111.28 kg CO_2e/ha). These simulation results highlight the critical importance of adopting residue management practices that avoid anaerobic decomposition to minimize agricultural GHG emissions.

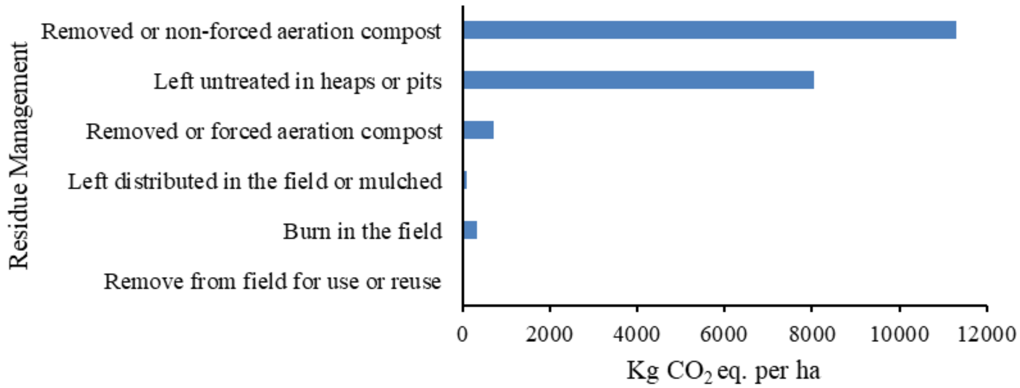

Fig. 4: Total CO_2-equivalent emissions per hectare under various residue management scenarios.

3.4 Environmental Impacts of Agricultural Activities Across Life Cycle Stages

Fig. 5 presents the comparative environmental impacts of key agricultural activities assessed under four major impact categories: global warming potential, eutrophication, air pollution, and ecotoxicity. Among the activities evaluated, fertilizer production contributed most significantly to global warming potential. This is primarily attributed to the high energy demands of fertilizer manufacturing and the resulting greenhouse gas emissions. Soil emissions, especially nitrous oxide (N_2O), also emerged as a major contributor to climate change impacts, reflecting the influence of nitrogen dynamics in soil microbial processes. Pesticide and herbicide production exhibited the highest impact under the ecotoxicity category, indicating the considerable environmental risk these chemical inputs pose to both terrestrial and aquatic ecosystems. In comparison, residue management and the use of field machinery demonstrated moderate contributions across all impact categories. These findings emphasize the importance of addressing emissions not only at the field level but also during upstream input production processes. Prioritizing interventions in fertilizer and pesticide manufacturing, as well as strategies to manage soil nitrogen emissions, is critical for reducing the environmental footprint of agricultural systems.

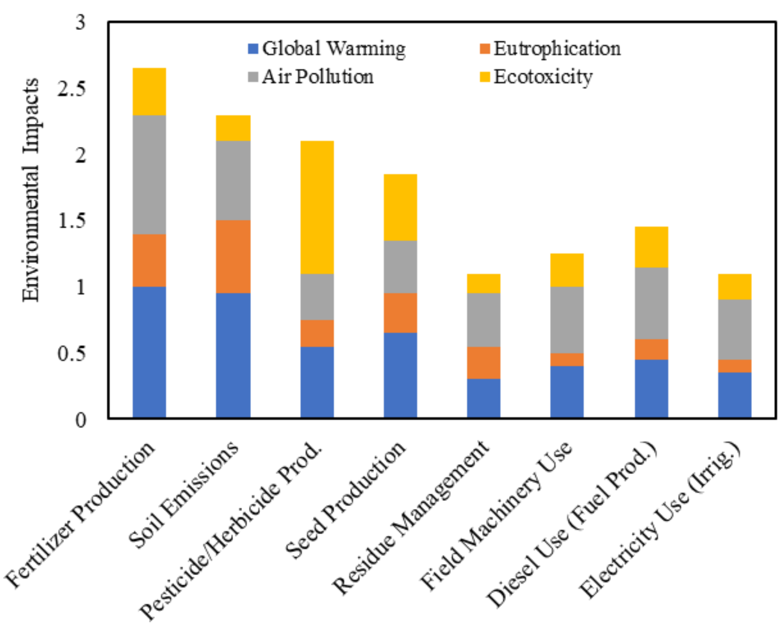

Fig 5: Environmental impacts of significant activities in a corn field

3.5 Uncertainty analysis and validation

To account for variability in emission factors and differences in field management practices among farmers, Monte Carlo simulations were employed along with correlation analyses to assess greenhouse gas (GHG) emissions. Parameters exhibiting the greatest influence on total GHG emissions were identified by correlation coefficients (ɵ) approaching ±1 (Fig. 6). The analysis revealed that yield-scaled GHG emissions were primarily influenced by emissions from agricultural soils, underscoring the dominance of this source in driving total emissions. Specifically, the emission factor for direct soil emissions demonstrated a strong positive correlation with overall GHG output (ɵ = 0.79–0.86), signifying its role as the most critical input in explaining emission variability. Conversely, contributions from the production of herbicides, seeds, and diesel were minimal, with these parameters showing the weakest correlations with total emissions. Fertilizer production and its field application rate also showed positive, though less pronounced, associations with GHG outcomes (ɵ = 0.18–0.28). This moderate sensitivity aligns with earlier findings indicating a weak relationship between fertilizer input levels and crop yield. These sensitivity patterns highlight agricultural soil emissions as a key focus area for mitigation strategies in crop-based GHG reduction efforts. Despite the use of precise field-level inventory data, such as application rates for fertilizers, irrigation, and seeds, as well as travel distances, yields, and input costs, uncertainty from soil-based emissions remained dominant, representing a core limitation of the analysis.

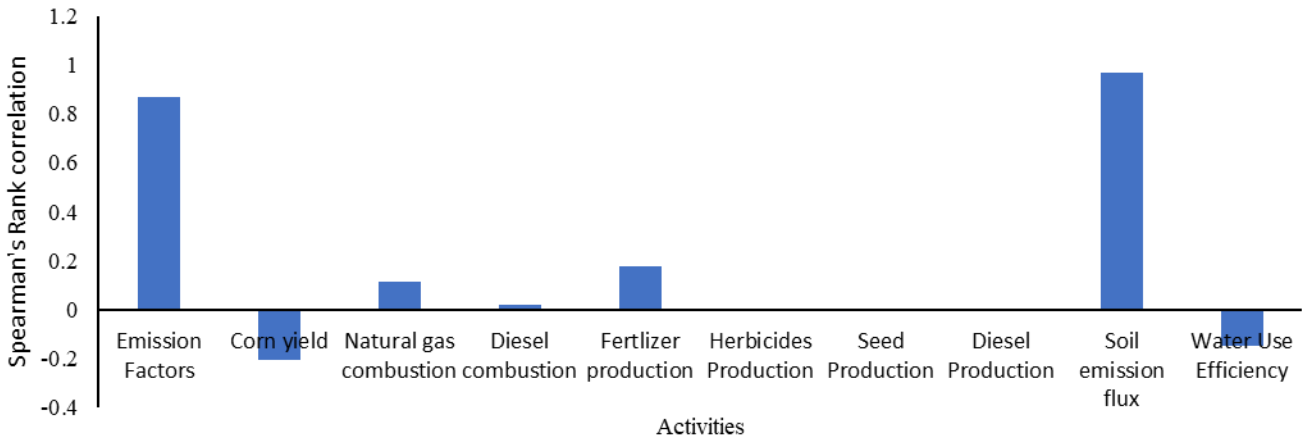

Fig. 6: Spearman's Rank correlation coefficients between yield-weighted total GHG emissions and various farm activities.

Direct measurements of greenhouse gas (GHG) fluxes (using static chambers and sample analysis using gas chromatography), particularly nitrous oxide (N_2O) and carbon dioxide (CO_2), were evaluated using regression analysis to assess the reliability and strength of model predictions against observed field data. The coefficient of determination (R^2) was used to quantify the proportion of variance in GHG fluxes explained by key environmental and management factors such as soil moisture, temperature, and fertilizer application rates. CO_2 emissions generally showed stronger model fits, with R^2 values typically ranging from 0.48 to 0.61, reflecting more stable and predictable flux patterns influenced by microbial respiration and soil temperature. In contrast, N_2O emissions exhibited greater temporal and spatial variability due to complex microbial nitrogen dynamics, resulting in lower but still informative R^2 values, commonly between 0.3 and 0.46. Statistical significance of these relationships was assessed using P-values, where values below 0.05 indicated strong evidence that the predictor variables significantly influenced GHG emissions. For instance, N_2O fluxes were often significantly correlated with soil moisture and nitrogen application rates ($P < 0.05$), while CO_2 emissions showed strong dependence on soil temperature and organic matter content.

4. Conclusion

The life cycle assessment highlighted the pivotal influence of nitrogen management on greenhouse gas (GHG) emissions in corn production systems. High nitrogen application rates significantly elevated emissions from both fertilizer manufacturing and subsequent soil-based N_2O fluxes. Additionally, residue management emerged as a critical determinant of the emission profile; anaerobic decomposition methods resulted in markedly higher GHG emissions due to elevated methane and nitrous oxide production. In contrast, practices such as residue removal or aerobic composting substantially reduced emissions. The model was most sensitive to the modeled GHG emissions from agricultural soil, which exhibited significant uncertainty in the emission factor. These findings emphasized the need for integrated and site-specific management strategies that prioritize optimized fertilizer application and climate-smart residue handling. Adopting such practices could have substantially mitigated the carbon footprint of corn production while maintaining or even enhancing yield outcomes. Furthermore, refining emission factor estimates and improving the precision of field-level GHG measurements supported more accurate modeling and better-informed policy decisions.

Acknowledgements

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